

Studies of the Earth's Deep Interior: Goals and Trends

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Citation: *Physics Today* **43**(10), 44 (1990); doi: 10.1063/1.881240

View online: <http://dx.doi.org/10.1063/1.881240>

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STUDIES OF THE EARTH'S DEEP INTERIOR: GOALS AND TRENDS

Profound opportunities for understanding the mysteries of the inner Earth lie within reach. But it will take a concerted interdisciplinary research effort to model the total dynamic Earth system.

Thorne Lay, Thomas J. Ahrens,
Peter Olson, Joseph Smyth
and David Loper

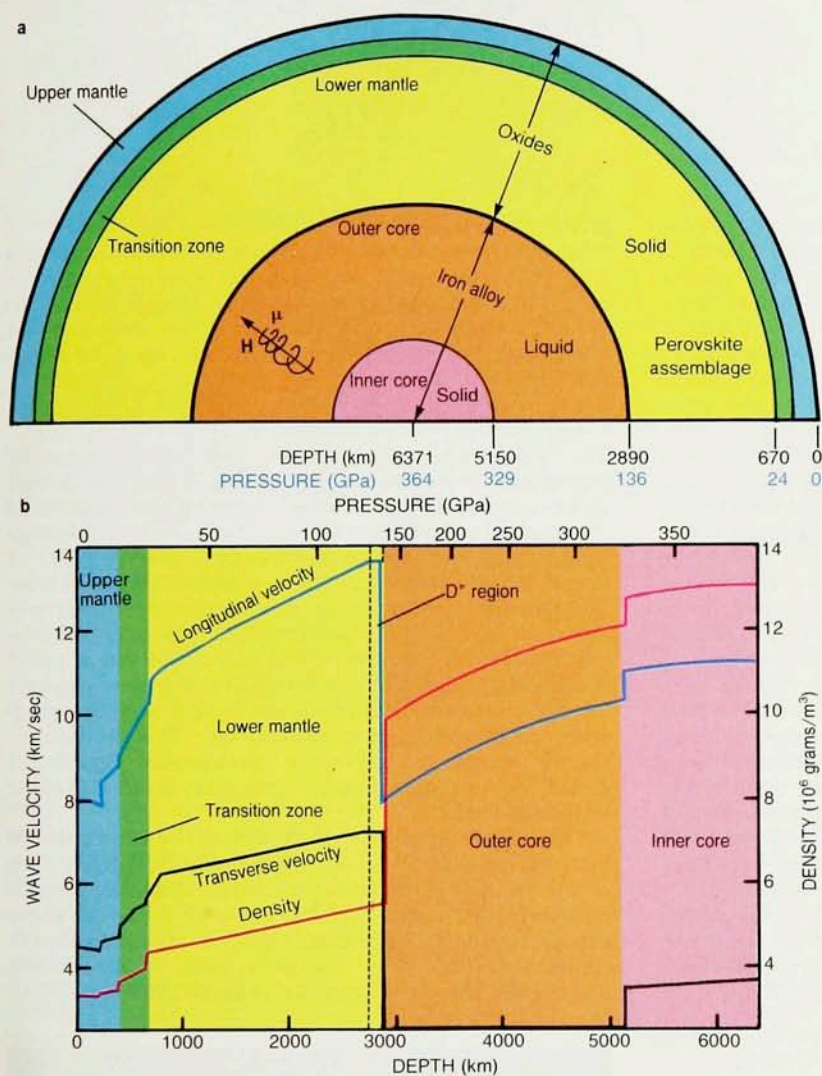
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Union Committee for Study of the Earth's Deep Interior.

The deep interior of planet Earth has long fascinated philosophers, scientists and fantasy writers, yet it remains inaccessible to direct scrutiny and thus largely enigmatic. Romantic notions about the interior are provocative, with crystal-filled chambers and pitchfork-bearing devils. However, the more scientifically based visions are just as alluring.

We now recognize that at least two great convective engines operate in the interior, driven primarily by thermal and chemical processes. These two engines are intimately coupled across a major internal transition zone, 2900 km deep, that connects the two vast regimes in the lower mantle and outer core. These regimes have distinct chemistries, dynamics and physical states. The core-mantle transition zone is believed to be a major thermal boundary layer and a repository for both light products expelled from the core and heavy heterogeneities that have separated from the mantle. The transition zone is also thought to be an active chemical reaction zone where core and mantle materials may be exchanged (see figure 1).

The deepest convection occurs in the molten iron-alloy core. The gradual growth by freezing of the inner core releases gravitational and thermal energy that drives the flow. The resulting motions of the electrically conducting fluid create the Earth's magnetic field by dynamo action, providing surface observers with a means to analyze the core flow patterns. In the overlying silicate mantle, a more sluggish convection of the entire vast rock mass occurs in either a layered or a mantle-wide system, driven by heat released from the cooling core, by secular cooling of the mantle rock and by the ongoing decay of internally distributed radioactive materials. This nonsteady mantle flow transports heat, dynamically deforms the internal and surface boundaries, modulates the heat flow out of the core (thereby influencing the core convection regime), and both creates and mixes chemical heterogeneities. The surface manifestations of this mantle convection—vertical and horizontal motions, volcanic eruptions, earthquakes and the evolution of continents and ocean basins—are described by the kinematic theory called plate tectonics.

Investigation of the Earth's internal regions requires



Cross sections of the Earth and its properties. **a:** Seismologically determined regions and pressures as a function of depth (100 GPa equals 1 megabar). The mantle and crust, consisting almost entirely of solid oxides, surround the molten outer core and the solid inner core. Cyclonic motions μ of the molten iron alloy making up the outer core generate the main geomagnetic field H . (Adapted from R. Jeanloz, *Annu. Rev. Earth Planet. Sci.* **18**, 357, 1990.) **b:** Average elastic parameters as a function of depth. The P-wave velocity V_p , S-wave velocity V_s and density ρ are determined from seismological analysis. The figure is based on the Preliminary Reference Earth Model. (Adapted from R. Jeanloz, in *Mantle Convection*, W. R. Peltier, ed., Gordon and Breach, New York, 1989, p. 203.) **Figure 1**

sophisticated remote sensing techniques, given that our measurements cannot reach far below the planet's surface. A rich body of geophysical inverse theory has evolved that is used to extract information about the interior from the broad spectrum of seismological, electromagnetic, geothermal and gravitational measurements. Yet we are only in the early stages of achieving a true understanding of the deep interior of the planet on which we live. The next major advance will be to move from the kinematic theory of surface motions to a more quantitative dynamic theory of the solid Earth system. Recognizing that successful dynamic theories will need to synthesize data and concepts from a variety of disciplines, Earth scientists have recently formed, under the auspices of the International Union of Geodesy and Geophysics, a Committee for Study of the Earth's Deep Interior to facilitate these cooperative efforts. This article will outline some of the interdisciplinary science opportunities at the cutting edge of solid Earth science and their relation to physics, mathematics, computer science and observational technologies that are arising as we work toward an understanding of the total dynamic Earth system, which includes as well

the evolution of the atmosphere and oceans.

Seismological opportunities

Perhaps the most remarkable achievement of geophysical investigations of the Earth's deep interior is that the laterally averaged density and the seismic velocities at any depth in the core or lower mantle are known to better than 1% accuracy. This is primarily a seismological achievement, resulting from analysis of seismic waves generated by near-surface earthquakes and explosions. Generally there are three types of elastic waves used to image the interior: compressional or acoustic (P) waves, shear (S) waves and longer-period surface waves, which can also be analyzed as free oscillations of the Earth as a whole. Given the quasielastic behavior of the Earth for short-time-scale transient loads, elastic waves spread through the interior from any source of deformational energy.

With a global distribution of deformation sensors, or seismometers, it is possible to record the waves excited by a large explosion or earthquake anywhere on the Earth's surface. The various waves, with periods ranging from nearly an hour to fractions of a second, travel throughout

the planet, refracting, reflecting and converting between wave types wherever they encounter changes in material properties. The complex wave field that results can be quantitatively analyzed to determine density and elastic properties at all depths in the planet. Condensed matter physicists may then use this information to narrow down the likely chemical composition and average state of the vast bulk of the Earth (figure 1a) for which we will never have a direct sample.

Were the Earth a tectonically inactive planet with only a radially varying structure, little work would remain for seismological investigations of the deep interior. However, our planet is a vigorous, dynamically active system, with motions arising from thermally and chemically induced lateral density variations. How can seismology divulge the dynamic state of the deep interior? In the mantle, the solid-state convection involves hot, upwelling regions of relatively low density and cooler, sinking regions of higher density. Typically, hot regions have lower seismic velocities, while colder regions tend to have higher velocities. Thus, by developing a three-dimensional image of the elastic structure in the mantle, seismology can map the present state of the evolving mantle flow regime. The lateral fluctuations in velocity that accompany thermal heterogeneity are at most a few percent of the average velocity at a given depth; therefore very-high-precision measurements and images are required.

Fortunately, there is another seismologically detectable property of the flow regime that can be measured. Shear stresses involved in flow can induce recrystallization and preferred orientation of the anisotropic minerals,

giving the mantle material a bulk anisotropy. Because of this anisotropy, the velocity of seismic-wave transmission depends on the angle at which the wave traverses the mineral assemblage. Using a variety of wave types with different directions of motion, we can measure the anisotropic fabric of the rock to help determine the actual flow regime.

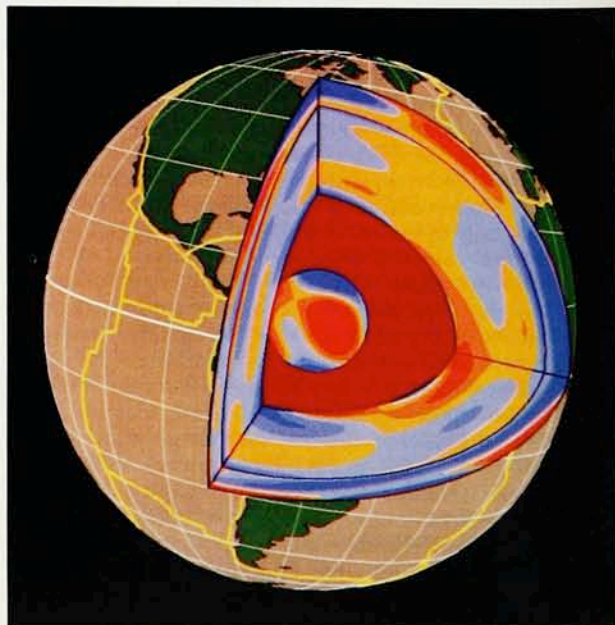
Three-dimensional imaging

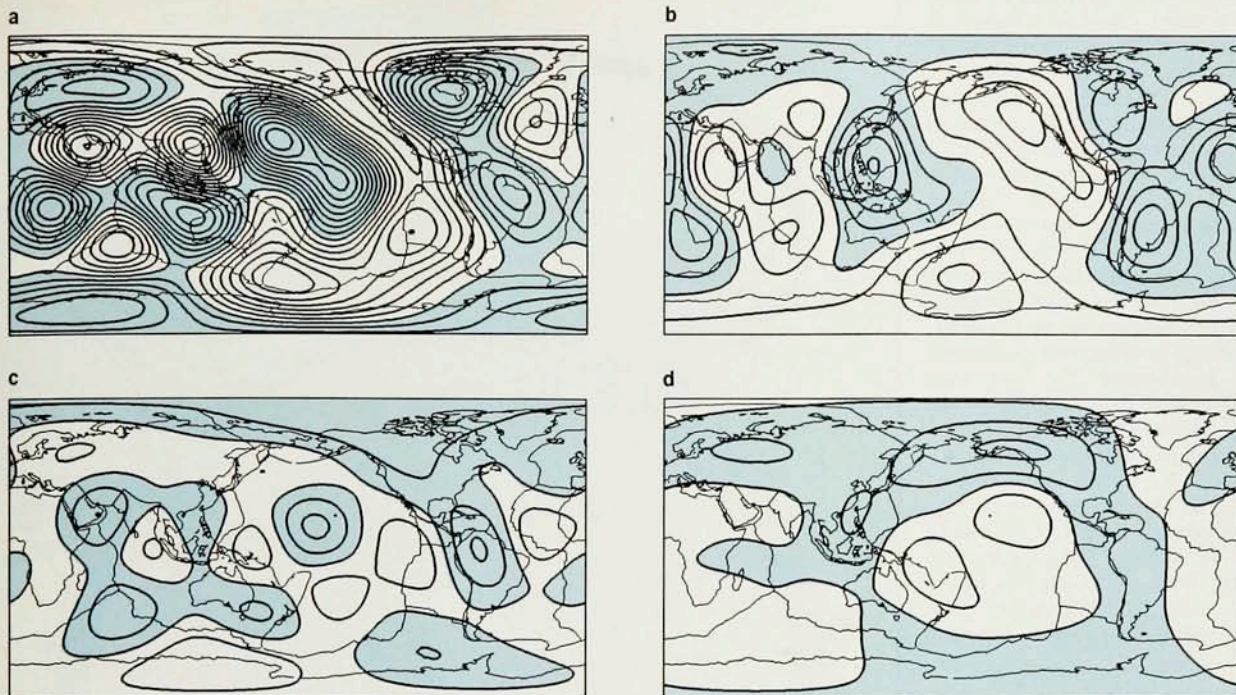
The 1980s brought the first three-dimensional images of the seismic velocities and anisotropy in the mantle and inner core (see figures 2 and 3), along with refinements of the detailed velocity structure near major internal boundaries such as the inner core–outer core, core–mantle and upper mantle–lower mantle transition zones. Three-dimensional imaging, which uses procedures collectively described as “seismic tomography,” has exploited the accumulated P- and S-wave data base of millions of travel times and thousands of waveforms as well as new, digitally recorded data sets of surface waves and their standing-wave counterparts, free oscillations. The sources for seismic waves are primarily earthquakes, distributed globally in midocean ridges, subduction zones and along strike-slip faults.

Seismic imaging has shown that in the outermost 200 km of the mantle (figure 3a) seismic velocities are very low in the vicinity of extensional surface tectonics, such as oceanic ridges, continental rifts and back arc basins above subducting slabs. What these features apparently have in common is that they are all regions of hot mantle upwellings. On the other hand, beneath older, geological

Seismic velocity variations inside the Earth. This three-dimensional image was obtained by seismic tomography. Blue regions have velocities that are faster than the mean value at that depth in the Earth; red regions have slower-than-average velocities. The figure shows S-wave velocity variations in the upper mantle, and P-wave velocity variations in the lower mantle and inner core. The velocities vary by as much as 10% in the upper mantle, but by less than 2% in the deeper regions. The outer core is homogeneous on this scale.

(From A. M. Dziewonski, J. Woodhouse, *Science* **236**, 37, 1987; © AAAS.) **Figure 2**





Lateral variations in S-wave velocity obtained by seismic tomography for layers at depths of 0–220 km (a), 400–670 km (b), 1022–1284 km (c) and 2630–2891 km (d). Shaded regions exhibit S-wave velocities faster than average; white regions show slower-than-average velocities. The contour interval is 0.5%. (From T. Tanimoto, *Geophys. J. Int.* **100**, 327, 1990.) **Figure 3**

ly more stable areas, such as continental shields and old ocean basins, one measures fast upper-mantle velocities, suggesting that the material has been cooling near the surface for a long time. Large-scale variations of anisotropy in the upper 200 km are consistent with the flow regime expected on the basis of surface tectonics as well. At greater depths, near 400 km (figure 3b), the lateral velocity variations are much reduced, and the spatial pattern is quite different. Areas of subduction (or convergence), such as the western edge of the Pacific Ocean, have the fastest seismic velocities at this depth, consistent with the presence of cold downwelling material. The Pacific and the Red Sea–East African Rift areas are the slowest regions near the base of the upper mantle.

The lower mantle (figure 3c and d) has long-wavelength, low-amplitude velocity variations that correlate with the long-wavelength geoid, or shape of the Earth. This region is believed to be relatively homogeneous in composition, with thermal variations producing the seismic velocity heterogeneity. Under the assumption that the heterogeneity is thermal in origin, the velocity variations can be mapped onto density anomalies that drive viscous flow. Density-driven flow throughout the mantle perturbs the internal and surface boundaries, with the net effects of density and boundary perturbations summing to give the geoid. Flow induced by lower-mantle heterogeneity may account for much of the long-wavelength geoid.

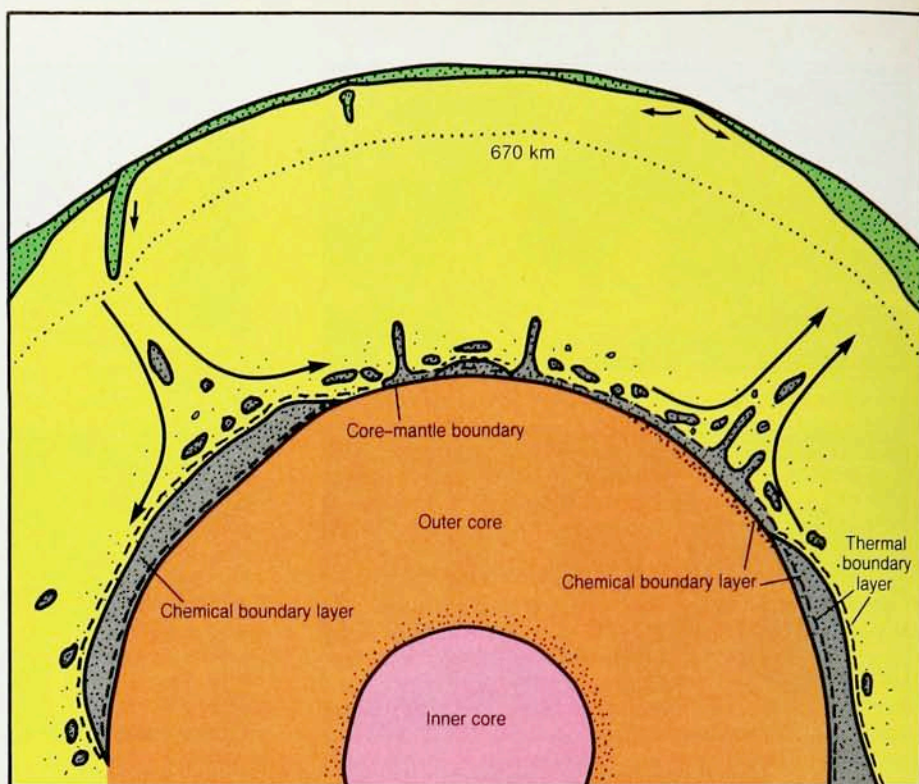
The base of the mantle (figure 3d) has circum-Pacific and polar bands of material with higher-than-average velocity that is probably colder than the surrounding material. The mantle is about 24 orders of magnitude more viscous than the core—resulting in much lower flow velocities—so the colder regions at the base of the mantle

are long-lived with respect to the core. The mantle temperature structure thus causes nonuniform heat flow out of the core, and may thereby influence the core convection pattern. There is no agreement yet about the presence of convection-induced relief on the core–mantle boundary, but some preliminary seismological results support the expectation that the boundary is depressed under cold mantle downwellings. Any such topography would mechanically couple the core and mantle, and in combination with thermal and electromagnetic coupling and rotation of the Earth, this interaction could influence the core convection pattern and the geometry of the dynamo-induced magnetic field.

The mode of mantle convection is still controversial. If the mantle is uniform in composition and if the effects of phase changes and pressure- and temperature-dependent properties do not introduce unexpected obstacles, the whole mantle should convect in a single layer. In that case, subducting oceanic slabs could sink to the core–mantle boundary and hot upwellings from this boundary could rise to the surface, perhaps under midocean ridges or hotspots. Alternatively, if the Earth accreted at high temperatures with efficient crystal–melt separation early in its history, the planet may possess segregated internal layers (in addition to the crust and core) of distinct bulk chemistry. In that case, slabs might bottom out near the base of the upper mantle (around 670 km deep), and hot upwellings might originate near this boundary as well, perhaps assisted by heating from below. Seismic imaging of the interior holds the key to resolving this fundamental debate, and vigorous research is under way to determine both the depths to which slabs sink and the depths from which upwellings originate.

While this first generation of three-dimensional

Core-mantle transition zone features, based on geophysical data. A heterogeneous chemical boundary layer is embedded in a thermal boundary layer produced by a large contrast in temperature between the core and mantle. Large-scale mantle circulation transports chemical heterogeneities to the base of the mantle and returns them to shallower depths by entrainment. Whether this circulation has a whole-mantle or a layered-mantle configuration remains to be resolved. Thermal plumes caused by instabilities in the hot thermal boundary layer may disrupt the chemical boundary layer. The dotted line represents the base of the upper mantle, which is roughly 670 km below the surface. (Adapted from T. Lay, *Trans. Am. Geophys. Union* **70**, 49, 1989; © American Geophysical Union.) **Figure 4**



seismological images of the deep mantle has yielded unprecedented interaction among seismologists, geodynamacists, mineral physicists and geomagneticians, the existing models are limited and not entirely in agreement with each other. Improvement of the models will require a better global distribution of modern digital seismic instrumentation, extensive development of new theory and procedures for analyzing seismic waves in complex three-dimensional structures, and new inversion techniques by which to determine the associated structures.

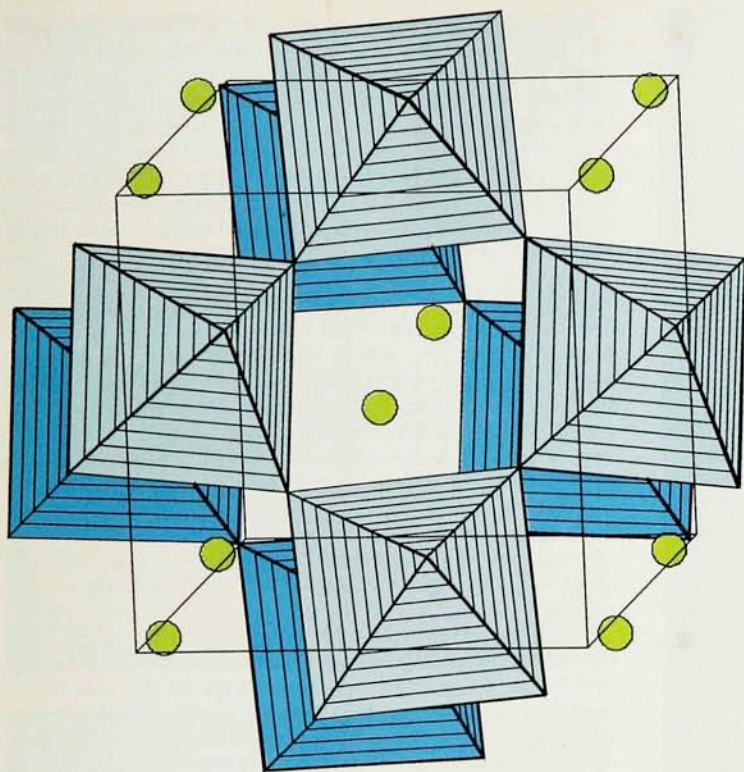
Global data acquisition efforts

Several important initiatives are under way that promise to provide a new generation of high-quality seismic data with which to improve our models. The first involves an upgrade of the global network of permanent seismic facilities. This effort is being coordinated in the US by the Incorporated Research Institutions for Seismology as well as by similar organizations in Japan, France, The Netherlands, Italy, Canada and Germany. These groups are deploying new digital instruments with far greater dynamic ranges and bandwidths than previous global networks. In addition, IRIS is developing complementary broadband portable instruments that can be deployed in flexible networks of up to 500 stations for high-resolution imaging of the crust and deep interior. Another data-acquisition effort, sponsored by SEDI, is the International Seismological Observation Period, during which seismographic station operators worldwide will report arrival times for the many secondary phases that are poorly reported at present. The ISOP should produce an improved data set with special sensitivity to deep-mantle and core structure.

Particularly exciting research problems that can be tackled with the new seismological data and analysis procedures include determination of the configuration of mantle convection (whole-mantle versus layered convection) and high resolution of the structure of the core-

mantle and outer core-inner core transition zones. Probably the most important questions to answer involve the scale of mantle convection. In particular, new techniques and data are needed to resolve the fate of subducted material that is transported into the transition region between the upper and lower mantle. A related question involves the depth of the source for anomalous volcanic centers (hotspots) such as Hawaii and Yellowstone, and how this might differ from the depth of the basaltic source feeding the globe-encircling midocean ridge system. Are hotspots fueled by deeper or shallower sources, and do they represent a different type of convection? There is also great interest in the extent of the cooled mantle roots under ancient continental crust, which have been proposed to extend as deep as 400 km. If this proposal is true, these continental roots must influence upper-mantle convective flow and may hold the key to understanding the early evolution of the continental crust.

The core-mantle boundary, like the Earth's surface, is believed to be a major thermal and chemical boundary (figure 4). Just as studying the surface has revealed the kinematics of plate tectonics, so will investigations of the base of the mantle reveal the flow structure and thermal character of this internal boundary layer. Broadband data from both permanent and portable arrays will have to be analyzed using three-dimensional inversion techniques to reveal the processes at the boundary. The outermost core is another poorly understood region, and improved resolution of its structure is vital for understanding the fine-scale features of the magnetic field and the role played by chemical and physical interactions between the core and mantle. Several major questions about deep Earth dynamics need to be resolved in the 1990s: Is there a stably stratified layer in the outermost core? Does the outer core have any rigidity? Is it a slurry? What is the topography of the core-mantle boundary? New high-resolution three-dimensional seismic imaging techniques that transcend current travel-time tomo-



Most abundant mineral in the Earth, MgSiO_3 in the perovskite structure. Polyhedra represent silicon in octahedral (sixfold) coordination with oxygen, and circles represent magnesium in irregular eightfold coordination with oxygen. Identification and characterization of this phase was one of the most significant advances of the 1980s in mineral chemistry of the Earth's deep interior. **Figure 5**

graphy methods are needed to resolve these basic questions.

It is the next generation of seismologists, drawn from the fields of applied mathematics, Earth sciences and physics, who will provide the answers to many of the basic questions about the current internal structure of the Earth and its dynamic state. The seismologist maps seismic velocities, densities, impedances and depths of boundaries. These can be converted to temperatures, compositions and crystal structures with the aid of laboratory measurements at high temperature and pressure and, in the case of boundary displacements, convection modeling in realistic systems. Thus it is imperative that seismologists work in close coordination with mineral physicists and geodynamicists to understand the entire system.

Mineral physics opportunities

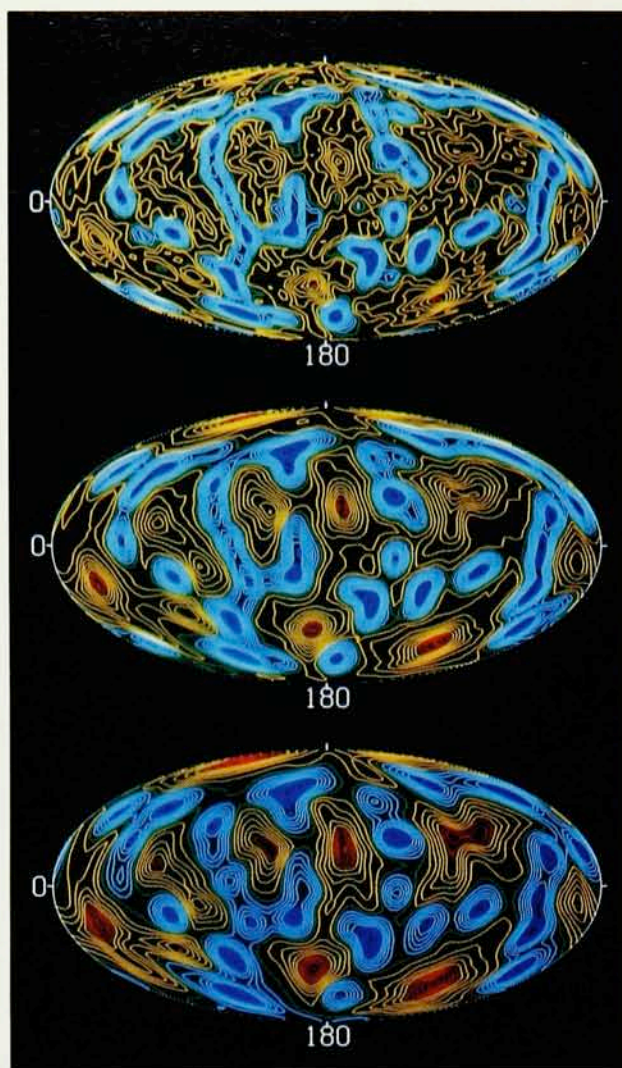
Knowledge of the elastic velocities and densities of the deep mantle and core is in itself insufficient to uniquely define the chemistry, temperature and rheology of the deep interior. To do so requires independent information on cosmochemical abundances as well as high-pressure, high-temperature experimental determinations of elastic properties of the materials that likely make up the deep Earth. It is also crucial to know the equilibria and the partitioning of major and minor elements among high-pressure phases. The results of investigations of these aspects of deep-Earth condensed matter physics have been combined with other geophysical data to provide spectacular advances in our knowledge of the internal composition and state of the interior.

For example, cosmochemical, electromagnetic and density observations in tandem with high-pressure experimental results provide compelling arguments that iron is the primary constituent of the dense core of the planet and that temperatures in the frozen inner core may exceed 7000 K. In addition, it is now recognized that a single

dominant crystal structure, silicate perovskite $[(\text{Mg,Fe})\text{SiO}_3]$ and, possibly, CaSiO_3 is pervasive in the lower mantle. (Figure 5 shows a representative projection of the perovskite crystal structure.) This conclusion is based on experimental demonstrations that the abundant rock-forming silicates containing magnesium, iron and calcium all undergo a transformation to a perovskite-like structure [with or without a rock-salt-structure phase of $(\text{Mg,Fe})\text{O}$] at pressures typical of depths of 670 to 2900 km in the lower mantle.

Whole-Earth geochemical models, largely based on cosmochemical abundances, provide important limits on the possible chemical composition of the deep interior. The Earth is generally considered to contain nonvolatile elements in nearly the same proportions as are found in primitive chondritic meteorites, in which the elemental relative abundance is similar to that of the Sun. Some geochemical models of the Earth have therefore attempted to match observed geophysical properties by starting with a chemical system in which the greatest uncertainties are in the proportions of the volatile elements, such as sulfur, rubidium, lead and copper. Experimental and theoretical analyses are needed to determine the distribution of elements under inner-Earth pressures and temperatures. It is also clear that total and partial melting processes are major factors in the evolution of the Earth's chemical distribution; hence much improvement in our understanding of complex melting processes is urgently needed.

New technologies and instrumentation are rapidly being developed for the direct exploration of experimental phase equilibria and major- and minor-element partitioning among high-pressure phases. Diamond-anvil-cell technology is advancing particularly rapidly and now permits studies of phase equilibria at pressures exceeding that at the center of the Earth. Laser heating procedures allow sample temperatures to reach as high as 6000 K. The cells are transparent over a wide range of the electromagnetic spectrum, including visible light and x rays; therefore



Chaotic thermal convection in a self-gravitating spherical shell of viscous fluid, obtained by numerical simulation. From top to bottom, the images are contours of radial velocity near the top of the shell (at a normalized radius of 0.89), at mid-depth (0.77) and near the base (0.66), in equal-area projection. Red denotes upwellings; blue, downwellings. Flow near the upper surface is dominated by arcuate sheets of sinking fluid, analogous to subduction zones in the Earth's mantle. At greater depths, the flow includes rising cylindrical plumes, analogous to thermal plumes from the Earth's lower mantle. Such plumes are thought to be the cause of volcanic hotspots such as Hawaii and Iceland. (From D. Bercovici, G. Schubert, G. A. Glatzmaier, *Geophys. Res. Lett.* **16**, 617, 1989; © American Geophysical Union.) **Figure 6**

studies of the equation of state, of Brillouin scattering (which measures elastic properties) and of crystal structure studies can be conducted *in situ*. Because the cells are small, new intense x-ray sources such as rotating-anode x-ray generators and synchrotron sources can easily be used.

In addition to the diamond-anvil cell, new large-volume experimental devices are undergoing rapid devel-

opment. The sample size in these devices is slightly larger than in diamond cells. Phase equilibria of upper-mantle transitions have already been explored, and studies of element partitioning at lower-mantle temperatures and pressures are under way. Currently available large-volume multianvil devices require very large presses to achieve the high pressures of interest; newer designs may allow smaller presses and also may permit researchers to make *in situ* observations by x-ray diffraction, rather than having to rely on quenched products.

Composition of the inner Earth

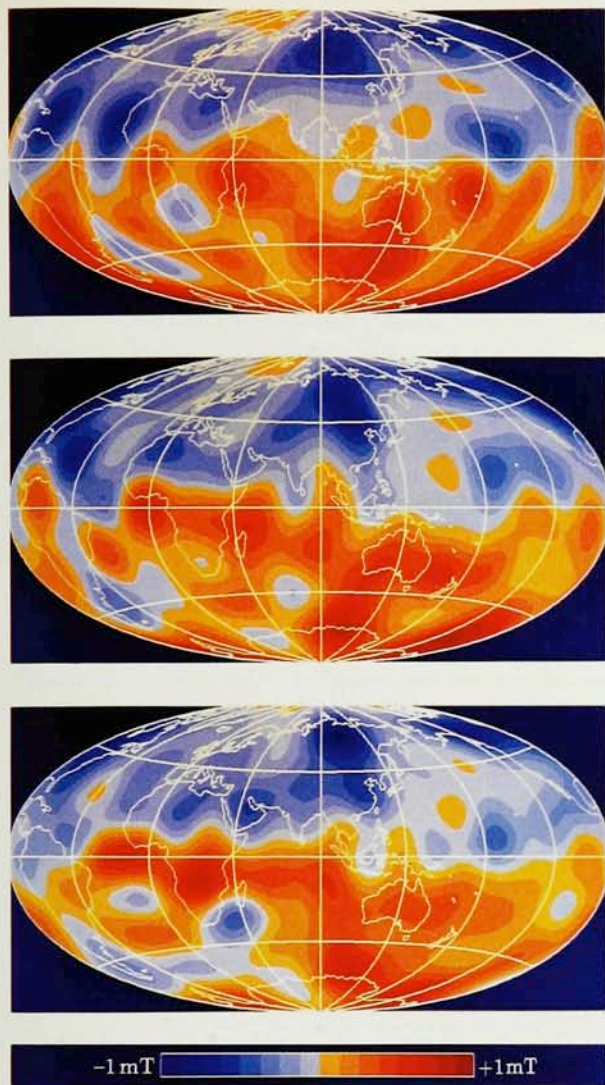
Theoretical modeling of the mineral chemistry of mantle phases is another rapidly developing field. Molecular-orbital bonding and numerical band-structure calculations have been used to predict silicate structures at high pressures, and more simplistic ionic models have been used to predict minor-element and stable-isotope distributions among various silicate phases. Analysis of silicate liquid structure using techniques such as molecular dynamics and Monte Carlo simulations is of growing interest. New computational capabilities are opening the doors for further development of such theoretical approaches.

Current questions whose answers will require the combined use of seismological and mineral physics data involve the compositions of the D" layer (at the base of the mantle), the lower mantle and the upper-mantle transition zone. In one standard Earth model, the mantle has a uniform composition, derived by mixing materials exposed at the Earth's surface. Such models give estimates that differ from those based on cosmic abundances. It has also been proposed that some or all of these regions differ from the shallow mantle. Seismic velocities and the depths of phase-change discontinuities can be used to place bounds on the major-element chemistry because they are direct measures of the mineral assemblages that are stable at a given pressure and temperature.

Precise measurements of phase boundaries and physical properties of minerals are required to convert seismic data to estimates of composition. The lower mantle represents about 70% of the mass of the mantle and therefore of the silicate portion of the Earth. Although seismic and mineral physics data are probably not adequate to determine the major-element chemistry unambiguously, one can probably test the competing hypotheses, namely, that the lower mantle is either "primitive," undifferentiated material (in other words, chondritic), the refractory residue resulting from removal of the crust and upper mantle or chemically distinct from cosmic or chondritic compositions.

There are many additional research frontiers in mineral physics associated with fundamental questions about the Earth's internal composition and state. Recent studies indicate that magma densities increase rapidly with depth, suggesting that some deep silicate melts may sink instead of rise and that melt compositions differ drastically at different pressures. The relative densities of mineral assemblages can also reverse at high temperatures or high pressures. There is great interest in whether there are ongoing chemical reactions at the core-mantle boundary, as has been proposed on the basis of preliminary experiments in the diamond-anvil cell. Laboratory experiments also are exploring whether or not deep earthquakes are the results of phase changes, by monitoring the transformation process *in situ* under high-pressure conditions and assessing whether elastic strain energy is released rapidly enough and in sufficient quantity to account for seismic-wave radiation from deep events.

Future study of the partitioning between core and



Magnetic flux at the core-mantle boundary, based on downward continuation of surface measurements for the years 1777 (a), 1882 (b) and 1980 (c). The magnetic-flux contours range from -1 (blue) to $+1$ (orange) millitesla. Note the substantial deviation from a simple dipole field, the stability of some flux features (the central Pacific) and the rapid evolution of other features (southern Africa). Characteristics of the core flow regime can be determined by analysis of these magnetic field images. (From J. Bloxham, D. Gubbins, *Nature* **317**, 777, 1985; © Macmillan Magazines Limited.) **Figure 7**

constraints on the deep interior into a dynamic model of the Earth system.

Geodynamics research opportunities

The primary objective in global geodynamics is to understand the great convective engines in the core and mantle: how they operate, how they interact and how they control near-surface processes at present and in the past. We are fortunate that the thermal conductivity of silicates is very low. This means that the mantle has a long memory of certain events in the past, such as the subduction of cold oceanic lithosphere. The thermal inertia of thick lithosphere sinking in the mantle lasts for hundreds of millions of years and is evident in high-resolution seismic images. Seismological images of the present Earth provide a snapshot of an evolving system, and any long-term projection of past and future configurations of that system requires an understanding of the dynamics. Conversely, the magnetic field is observed to change so rapidly that it is clear that the core flow regime is very complex and time dependent. Fortunately, some history of this system is recorded in the paleomagnetic record. Geodynamicists draw upon seismological and geomagnetic information to obtain boundary conditions for the development of an Earth system model.

Numerical simulations of thermal convection using supercomputers have recently provided new insight into the structure of large-scale motion in the mantle. The pattern of thermal convection in a spherical shell of viscous fluid (see figure 6) is geometrically similar to that actually imaged by global seismic tomography. This consistency is reinforced by tomographic models to predict the distortion of the surface gravitational field caused by lower-mantle flow. Convection, driven primarily by mantle radioactivity and secular cooling and secondarily by release of core heat, consists of linear, sheet-like descending flows and columnar upwelling plumes. The next generation of supercomputers will enable numerical simulations of convection with realistic values for all of the thermodynamic and transport properties of the mantle and with full time dependence in a spherical geometry.

It will be a great challenge for computational geodynamicists in the coming years to incorporate the physics of the near-surface lithospheric plates (the upper thermal, chemical and mechanical boundary layer of the mantle) into the convection models. Though this problem presents both conceptual and numerical difficulties, its solution will permit us to investigate plate tectonics processes starting from first principles.

Another challenge is to understand how thermal and chemical effects interact in mantle convection. The dynamical results of thermal and chemical heterogeneity appear to be about equally important in governing the

mantle reservoirs of the naturally radioactive elements uranium, thorium and potassium is particularly important because these elements control the distribution of heat generation in the Earth. One school maintains that the radioactive elements in the crust were stripped out of only the upper mantle, leaving a radioactive "primitive" lower mantle. Some convection and mass-balance calculations seem to rule out this model. At the other extreme, it has been proposed that most of the radioactivity in the lower mantle has been stripped out and deposited in the crust and upper mantle.

Numerous new high-pressure minerals have also been synthesized. Condensed matter physics at high pressure is potentially much more rewarding, particularly for new materials, than the vacuum and low-gravity synthesis popularized by NASA.

Key to the resolution of these problems is the measurement at high pressure and temperature of the thermodynamic parameters—thermal conductivity, viscosity, electrical conductivity, thermal expansion and specific heat—of lower-mantle and core minerals. The effects of volatile elements must be experimentally and theoretically explored, and the physics of melting quantified as well. With such information in hand, we will be able to integrate the seismological and mineral physics

mantle's evolution. The existing paradigms for mantle flow, involving either stratified convection or whole-mantle convection, both appear to be flawed—either that, or the present computations are overly simplistic. A new perspective, incorporating a more complex form of three-dimensional mantle dynamics, is needed.

Understanding the mantle flow regime will also require advances in our knowledge of the core-mantle transition region. Long-time interaction between the core and mantle is dominated by heat transfer, and we expect that the strong temperature contrast results in a major thermal boundary layer. It has long been argued that mantle plumes originate in this transition zone, primarily as a result of boundary-layer instabilities, but small plume-like features in the lower mantle have not yet been resolved by seismic tomography, and there is little direct evidence for this hypothesis. Plumes may originate from upper-mantle transition-zone boundary layers or even from temperature-dependent phase boundaries, with melting, for example, providing the dynamic instability. Establishing the actual source region for thermal plumes is one of the important tasks for the 1990s. Investigation of the dynamics of mantle upwellings and their mode of ascent and understanding their longevity requires modeling variable-viscosity convection in three dimensions, which is now becoming feasible through large-scale numerical simulation.

Angular momentum transfer

Angular momentum as well as heat is exchanged at the core-mantle boundary. The primary coupling mechanisms for this angular momentum transfer could be Lorentz forces acting on the conducting lower mantle, pressure forces associated with topographic variations at the boundary, or some combination of the two. Time variability in these mechanisms controls length-of-day fluctuations and may contribute to the excitation of the Chandler wobble, the free precession of the Earth. To quantify the role of these mechanisms it is necessary to know the shape of the core-mantle boundary (which can be determined from nutation observations and seismic tomography), the relative positions of the core and mantle rotation axes, the instantaneous velocity distribution of the core fluid near the boundary, and the magnetic field within the core. This is clearly an interdisciplinary activity.

The most important geodynamic problem associated with core flow is to understand how it produces the magnetic field by dynamo action. The outer core flows so rapidly that it is unlikely that any seismically observable lateral variations can be imaged. Instead, we must rely on magnetic field observations to determine the flow. The field, however, is very complex and time dependent (figure 7) and is not simply related to the flow regime. It is now understood that the important sources of core motions are fractional crystallization of the iron-rich inner core and spatially variable heat loss at the core-mantle boundary. One possibility for a new understanding is to establish the connection between lower-mantle structure, which controls the core-to-mantle heat flow, and the rapidly varying geomagnetic field structure arising from core flow just below the boundary.

Important questions associated with the core flow regime include: How does the magnetic field reverse, as it has done frequently in the past? What is the cause of dipole wobble? How strong is the "hidden" toroidal part of the magnetic field? It is critical to determine the electrical conductivity in the mantle and the degree to which the mantle screens out the magnetic field. Not only do we need new computational approaches, but the

observational base for resolving these questions requires improvement. Space-based global field monitoring is needed for investigating the short-term dynamo behavior, the electrical properties of the lower mantle and the energy exchange between the core and mantle caused by electromagnetic torques. Longer-time-scale observations, on the order of 10 000 years or more, can be made paleomagnetically, by analysis of lava-flow and sediment sequences. Coordinated paleomagnetic efforts are needed to resolve the spatial and temporal magnetic field structure during two critical intervals: over the past 20 000 years and during the most recent polarity reversal, which occurred about 700 000 years ago.

The development of comprehensive dynamic models for the mantle and core systems will require a coordinated multidisciplinary effort. Basic contributions will have to come from computer science, geochemistry and all branches of geophysics. Extensive theoretical developments in fluid mechanics and magnetohydrodynamics are also required, along with mathematical formalisms for handling the intrinsic nonuniqueness in inversions of geophysical data. Geophysical fluid dynamics studies have always taxed available computing capabilities to their limits, and it is fair to say that present supercomputers are not adequate to address current problems in the physics of the Earth's interior. This applies both to the accurate calculation, from first principles, of the properties of silicates and metals under extreme conditions and to convection in spherical shells with temperature- and pressure-dependent properties, variable radioactivity, phase transitions and mobile surface plates.

When these calculations are done, we can perform the ultimate planetary calculation: construction of a planet—including accretion, melting, cooling, crystallization and gravitational separation of components—from a cooling, condensing planetary nebula. All current Earth models start from an Earth of the present size and ignore the traumatic events that occurred prior to the geological record.

Making an impact

The primary objective of geophysics is to develop a unified model for the dynamic Earth system, encompassing the planet's thermal, chemical and dynamical structure. Many disciplines—spanning the range from computer science to field geology—contribute to this effort, and there are extensive research opportunities for significant contributions in many areas. Because the field is so young and so rapidly developing, individual contributions may have a primary impact. The mysteries of the deep interior will only succumb to a broadly based approach, drawing on state-of-the-art developments in all of the aligned fields. Recent efforts to promote communication among the fields have led to the creation of the national and international Committees for Study of the Earth's Deep Interior, which sponsor meetings, workshops and synoptic review articles like this one. The many fascinating problems associated with remotely determining the inner workings of Earth will continue to provide challenges for the next generation of scientists.

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We appreciate the many helpful comments provided by Don L. Anderson. This is contribution number 97 of the Institute of Tectonics and C. F. Richter Seismological Laboratory at the University of California, Santa Cruz. Lay received support from NSF grant EAR8451715. Information on the Committees for Study of Earth's Deep Interior of IUGG and the American Geophysical Union is available upon request from David Loper, Geophysical Fluid Dynamics Institute, Florida State University, Tallahassee, FL 32306-3017.